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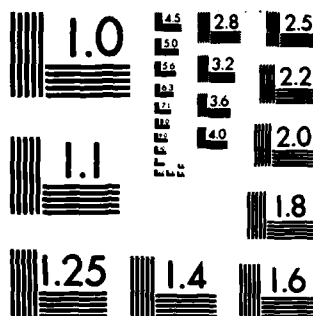
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ENGINEERING-PSYCHOLOGY RESEARCH LABORATORY

University of Illinois at Urbana-Champaign

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**The Integration of Information from
an Analog-Visual Display:
The Role of Dimensional Integrality**

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Christopher D. Wickens

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Abstract

The integration of information from several sources often proves to be an overwhelming task for the human decision-maker. It is proposed, however, that in such an information-integration task, the demand on the human's limited information processing resources will be lessened to the extent that the relevant information is displayed in proximity. In the ¹⁹⁷³ present report, "proximity" is defined by the degree to which the analog-visual dimensions representing the information are integral. Twenty-four subjects each monitored two dynamic systems over the course of three 2-hr sessions. Each system consisted of a single output, the value of which was determined jointly by two inputs. Two analog-visual displays--a bar graph and a triangular "object" display--were used to present the system ^{input/output} I/O information to subjects. Use of the triangular display resulted in more rapid detection of system failures at three levels of task difficulty.

*Additional keywords: multivariate analysis,
computer graphics, data displays,
statistical analysis.*

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THE INTEGRATION OF INFORMATION FROM AN ANALOG-VISUAL DISPLAY:

THE ROLE OF DIMENSIONAL INTEGRALITY

C. Melody Carswell and Christopher D. Wickens

The aquisition and manipulation of information from multiple dynamic displays is a task human operators are encountering with increasing frequency as technological systems continue to evolve. A number of observers have emphasized what they see as a fundamental change in the function of the human in relation to his or her technological surroundings, a change from functioning as the direct controller of a small number of system elements to the role of supervisory controller of multiple parameters of numerous subsystems (e.g., Van Cott, 1984; Sheriden & Johannsen, 1976). This perceived shift in human function has engendered increasng concern with designing displays to help circumvent human limitatons in tasks such as detection and diagnosis, essential components of the human's new role as a supervisory controller.

The present urgency for fitting display formats to the demands of numerous new tasks has been complicated by continuing developments in display technology. These developments provide the system designer with many alternative methods of presenting information, including voice synthesis devices and complex computer-generated graphics. But this increase in alternatives simply exacerbates the difficulty of the design decisions related to knowing which display will best support human information processing in a particular task. Psychological research has indeed shown that display format can have substantial effects on

performance, and these studies indicate that design decisions should consider such factors as Stimulus-central processing-response compatibility and attentional resource competition (Wickens, Sandry, & Vidulich, 1983; Wickens, Vidulich, & Sandry-Garza, 1984). However, important design decisions may not be restricted to such radically different formats as spoken numerals, written words, graphical representations, and tones. More subtle differences between different displays may also have significant impact on human performance and ultimate system utility. In particular, differences amongst various types of analog-visual (graphical) displays may have considerable implications for performance.

The intent of the present report is to focus on the task confronting the designer who decides that graphically presented information is desirable in a particular context. The capability, variety, and availability of computer-generated graphics has increased rapidly in recent years, making the choice of a specific technique relatively formidable. The traditional techniques--bar graphs, line graphs, pie charts and scatter plots--are readily available. But in addition, newer graphical representations of multivariate data are also coming into use. These new techniques include glyphs, metroglyphs, and k-sided polygons (reviewed by Fienberg, 1979), as well as Fourier blobs (Andrews, 1972), castles (Wilkinson, 1981), and trees (Kleiner & Hartigan, 1981). One technique which has received much attention is the use of faces as data displays (Chernoff, 1973). The different features of a caricature face have been used to represent multivariate information about such diverse subjects as Soviet foreign policy in African

nations (Wang & Lake, 1974), planetary craters (Pike, 1978), personality measures (Jacob, 1978), and corporate finances (Moriarty, 1979). While most of these graphical techniques have been employed to represent static information, a few efforts have been directed toward multivariate representations of dynamic information. For example, Wood, Wise, and Hanes (1980) and Peterson, Banks, and Gertman (1981) have explored the use of polygon-displays of safety parameter values in nuclear reactors.

The number of graphical techniques now available, as well as the likelihood that new variants will continue to appear, emphasizes the need to find highly generalizable guidelines for predicting what sort of analog-visual display will be most beneficial for particular classes of tasks. In order to attain this goal, distinctions relevant to the information processing demands placed on the operator must be made--distinctions both among the different displays and among the different tasks for which they will ultimately be used.

Display Integrality/Separability

One technique for categorizing different types of graphical displays is derived from research on perceptual organization. The essence of this categorization is the observation that although the physical world can be parsed in an infinite number of ways, some combinations of stimulus features or dimensions seem to be perceived together as a single unit while other dimensions remain separated as distinctly different parts of the perceptual array. Gestalt psychologists placed much emphasis on the problem of why some parts seemed to group together in a more indivisible way than did

others. Even though the highly phenomenological research methods used by these researchers fell into disuse, the fundamental questions they posed have remained of interest. Information processing psychologists, for instance, have attempted to operationalize the Gestalt concepts by relating performance in a number of experimental paradigms to the differing relationships that may hold amongst stimulus dimensions (see Pomerantz, 1981, for review of this methodological transition). Meanwhile, other researchers have taken a primarily psychophysical approach to studying psychologically separable and inseparable stimulus elements (e.g., Cheng and Pachella, 1984).

Perhaps one of the most widely utilized approaches to studying the independence of some stimulus dimensions and the relative cohesiveness of others has been by examining the performance patterns related to either "integral" or "separable" dimensions. It is this classification which several groups of researchers have used to distinguish different types of graphical displays (e.g., Jacob, Egeth, & Bevan, 1977; Goldsmith & Schvaneveldt, 1981; Casey, Kramer, & Wickens, 1984). On a subjective level, integral dimensions are those that seem to be processed together, that are automatically grouped, such as the height and width of a rectangle. Seperable dimensions are not so readily conjoined, as is the case with the hue and size of a color chip. The results of several performance measures converge to distinguish these two types of dimensional relationships operationally (e.g., Garner, 1970, 1974). For instance, a task quite commonly used to demonstrate the differential effects of integral and

separable dimensions on information processing is the speeded classification of a single dimension. Subjects are presented with a number of stimuli, each of which they have to sort into one of several categories based on the perceived value of a single dimension. However, a second dimension is also varied by the experimenter. Subjects are instructed to ignore this second "distractor" dimension and make their categorizations based only on the target dimension. Garner and Felfoldy (1970) found that when there was a correlation between the target and distractor dimension, there was an increase in classification speed over the case when the distractor dimension remained constant. This was the case, however, only for some pairs of dimensions. In particular, it seemed to be the case for those dimensions that seemed more subjectively cohesive. For those same dimensional pairs, when the value of the distractor dimension was varied orthogonally with the target, classification speed was impaired. Thus, for some dimensions, performance was systematically affected by the distractor dimension even though the subjects were told to ignore it. These dimensions were said to be integral dimensions. Other dimensional pairs which showed no intrusion of the distractor dimension on the target were labeled as separable dimensions. Other techniques, including multidimensional scaling and absolute judgment of multidimensional stimuli (Garner, 1970), as well as visual search and texture segregation (Triesman and Gelade, 1981), have also been used to demonstrate the integral vs. separable distinction.

The distinction between integral and separable dimensions has been used to distinguish the various graphical techniques used to present multivariate

information. Figure 1 shows a sample of these different techniques arranged on the basis of their likelihood of utilizing integral vs. separable stimulus dimensions. These distinctions are based primarily on the assumption that several dimensions of what intuitively seem to be a single object are more likely to be integral than several dimensions each forming part of a different object. Or, as Garner (1976) states, the inclusion of dimensions in a single figure is probably a necessary condition for integrality, even if it is not a sufficient condition. Thus, those graphical techniques utilizing several dimensions of a single object to display multiple variables are more likely to be integral. For example, the Chernoff display uses such dimensions as size and shape of a face, nose size, and direction of gaze to represent the values of multiple variables. These graphical techniques, defined by single objects, are often called "object displays". Displays such as the traditional bar graph, on the other hand, can use the same dimension (height) of several different objects (rectangles) to convey multivariate information. The bar graph, therefore, has been classified as a separable display.

Comparisons of the more integral object displays to more separable graphical techniques have generally shown the object displays to facilitate performance on a variety of tasks (e.g., Wilkinson, 1981; Jacob et al., 1976). The advantages of the object displays have been attributed to the integration of information that is achieved by the spatial coherence of the represented information (Naveh-Benjamin and Pachella, 1981). Or, according to Jacob et al. (1976, p. 189) ". . . if the data and their

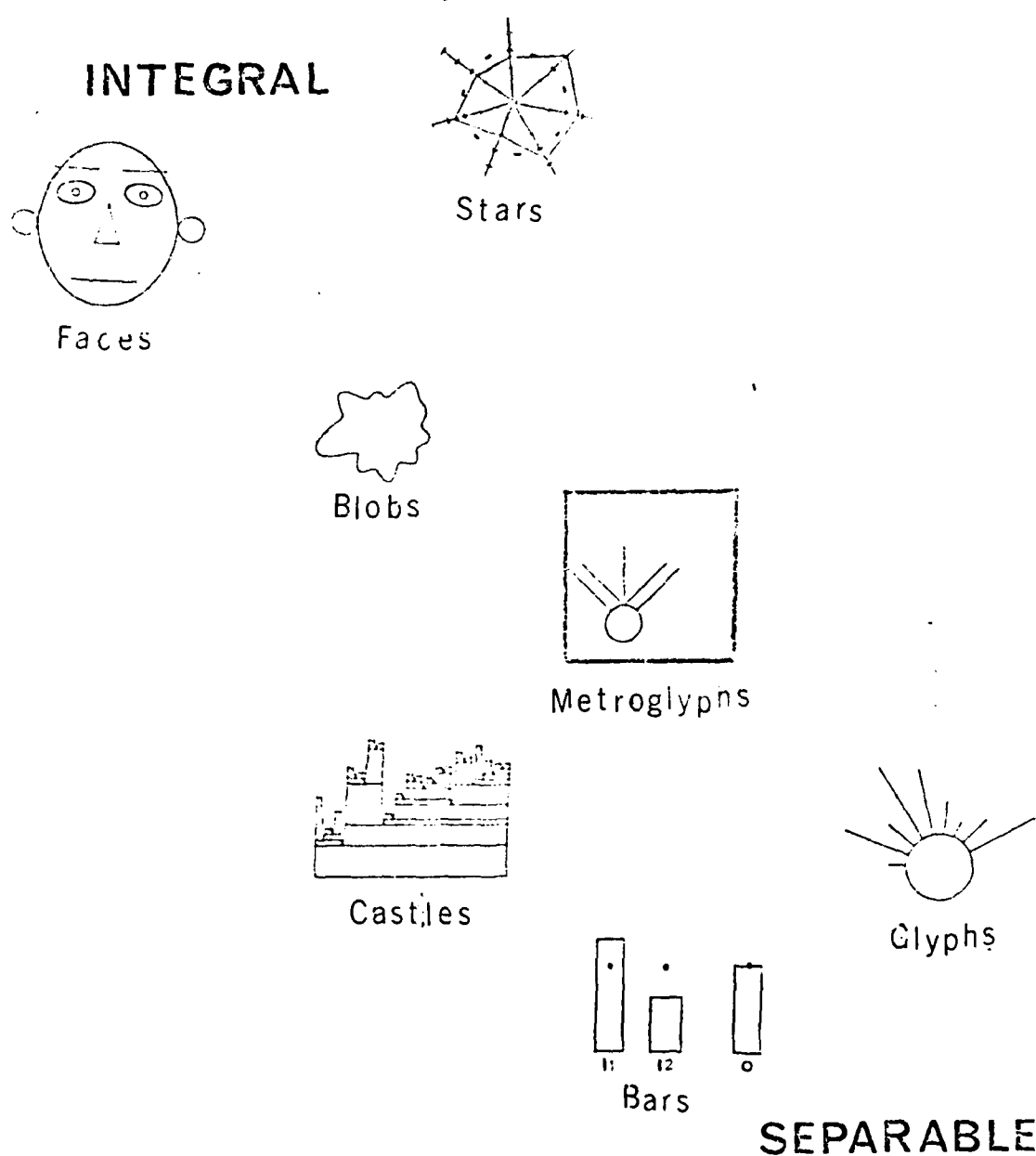


Figure 1: Examples of multivariate graphical techniques, ranging from the more integral varieties (upper left) to the more separable formats (lower right).

interrelationships are immediately apparent, as in a well-integrated pictorial display, then something akin to perceptual recognition may replace the logical exercise (of diagnosis)". That is, the more integral displays take advantage of the holistic properties of object perception, avoiding some of the time-consuming sequential processing associated with such "higher" functions as diagnosis or concept formation (see Garner, 1976, for examples of integrality effects on concept formation). While a considerable body of research supports the concept of the integral display, most of this has been carried out with relatively static tasks (i.e., variables are discretely updated on different trials). Few have examined whether corresponding advantages exist for dynamic tasks with continuously changing variables.

Though the benefits of object displays have been documented, the limitations of these displays have been less well described. In the context of nuclear power displays of safety parameter information, Peterson, Banks, and Gertman (1981) found that while a polygon ("star") display was superior for a failure detection task, it was associated with no such advantage for a failure localization task. Other authors (Naveh-Benjamin and Pachella, 1981; Wickens, 1984) also suggest the potential for "filtering decrements" which might occur in tasks where subjects needed to attend selectively to certain elements in order to perform optimally. In summary, the degree to which the more integral object displays may be beneficial to performance probably depends on the nature of the task for which they are used. In response to this concern, Wickens and Boles (1983) have suggested that a

limiting requirement for effective use of an object display may well be the degree of integration required to perform the task.

Task Integration

A task is said to require integration if the various sources of information displayed to the individual must be combined into a single mental model in order for an appropriate response to be made. Different tasks are apt to require different degrees of integration, with one extreme case being where all display elements must be combined, compared or considered in some way. At the other extreme, display elements may be responded to independently of one another and may, in essence, be seen as separate tasks. Figure 2 represents the continuum of task integration and the hypothesized relationship between this factor and display integrality (Wickens and Boles, 1983). To the extent that a task requires integration, then, there should be a benefit for the relatively integral display techniques. This advantage should not be obtained, or should even be reversed, when the variables displayed require little or no integration. In other words, if dimensions of a display are integrated at an early stage of information processing, perhaps preattentively as integral dimensions are believed to be processed (Triesman and Gelade, 1980), then this process may be substituted for the more time-consuming processes needed for later resource-demanding integration. This would result in a benefit for use of the more integral displays for tasks in which integration of the components must occur at some level of processing. Non-integration tasks would, however, not be benefitted by this display condition since the dimensions

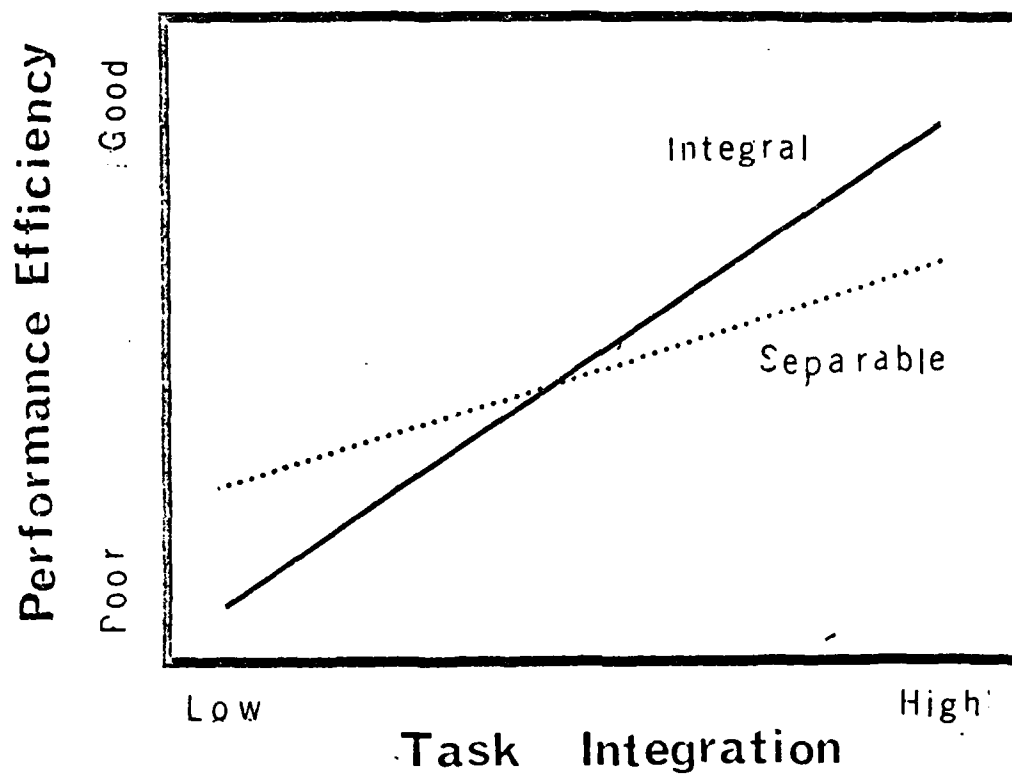


Figure 2: Proposed relationship between task integration (low vs. high) and display format (integral vs. separable) for predicting performance efficiency (adapted from Wickens & Boles, 1983).

would need to be "uncoupled" in order for the subject to perform the task, a process presumably requiring some effort.

Hypothesis

The experiment reported below is an attempt to test the proposed relationship between performance on a continuous integration task and tegrality. That is, the relation seen in the right half of Figure 2 will be tested. A task of monitoring the dynamics of a simulated energy or chemical process to detect periodic failures is used. This task, requiring integration of information from several sources, is tested using both an integral and separable analog-visual display. It is hypothesized that the more integral display should be associated with superior performance.

Methods

Subjects

Twelve male and twelve female right-handed subjects, ranging in age from 18 to 30 years, participated in the study. Subjects received \$3.50/hr during an initial practice session. During the following two experimental sessions, they were paid \$2.00/hr plus additional pay bonuses awarded on the basis of performance.

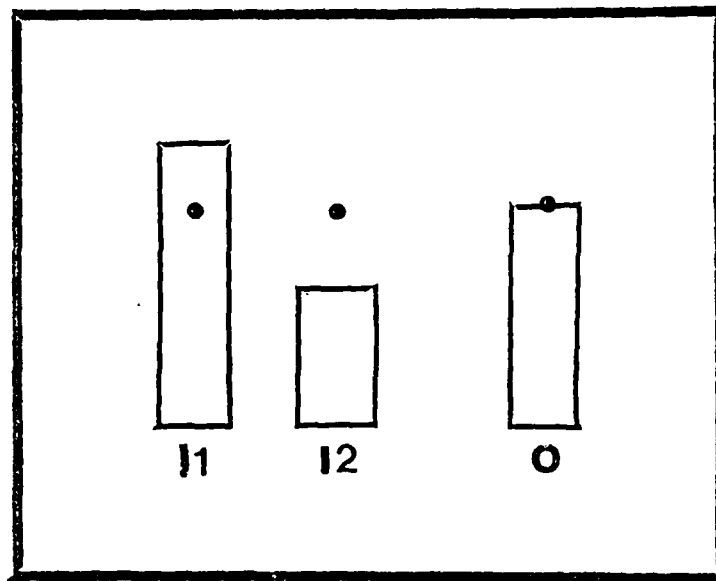
Tasks

Subjects were required to monitor the operation of two independent, dynamic "systems". Each system consisted of a single output, the value of which was jointly determined by two inputs. The subject's task was to

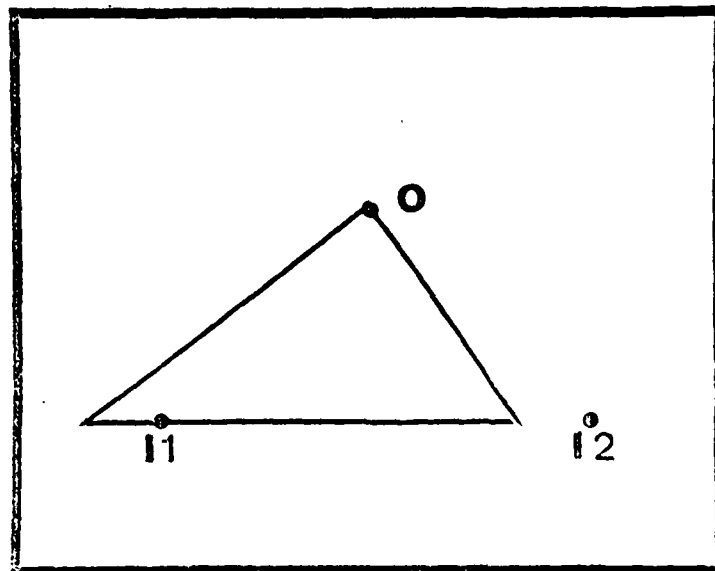
detect any deviation from normal system operation. This objective required subjects to integrate the currently displayed system inputs according to the rules they had learned during training, rules governing the "system dynamics". This integrated value, an estimated output value, must then be compared to the current output actually displayed for that system. If this output corresponded to the subject's generated (i.e., predicted) value, then the system could be assumed to be functioning normally. However, if the predicted system response did not match the displayed response, the subjects were required to indicate that the system was failing. Such failure detections were made by pressing one of two buttons corresponding to each system.

Displays

Two types of analog-visual displays were used to represent the monitored systems. In Figure 3, the inputs and output from a single system are shown using both displays. The first of the two displays was a traditional bar graph (Figure 3a). Each system was represented by three rectangles (or "bars"), the height of each representing the value of one input or output variable. The second display (shown in Figure 3b) was a triangular "object display". This display was similar to the iconic display which has been used to present safety parameter information in nuclear power plants (Wood, Wise, and Hanes, 1981). The triangular display utilized the distance of each of the three vertices from an anchor point centered on the triangle's base to convey the status of the three system I/o variables. That is, the distance of the left bottom vertex from the central point



(a)



(b)

Figure 3: The two types of displays used in the present experiment: (a) the separable bargraph, utilizing the height of three rectangles to represent the two input variables (I_1 and I_2) and the output (O) of a single system; and (b) the integral triangle display, utilizing the distance of the three vertices from a zero = point centered on the triangle's base to represent the same inputs and output.

represented the value of the first input variable, the distance of the right bottom vertex from the anchor point represented the second input value, and the value of the output was represented by the height of the triangle. For both types of displays, reference points (actually appearing as dots on the displays) were provided to specify the mean values for any given parameter. This triangular display, in comparison to the bar graph, was assumed to provide a greater degree of integrality among the dimensions used to represent system parameters. The three dimensions used to represent this information in the bar graphs were considered relatively more separable. Three dimensions of one object were used in the triangle display; one dimension of three objects was used in the bar graph display.

System Dynamics (for normal operation and failures)

Table 1 gives a formal description of the different dynamics used to generate an output with two inputs. The equations listed in the left column are those descriptive of the system dynamics that subjects were taught to expect as normal. Those in the rightmost column are the equations used to generate outputs during a simulated failure. The two inputs (I1 and I2) were slow, semi-random functions, uncorrelated with one another. These inputs were multiplied by coefficients (a, b, c, or d) and then either summed or multiplied to yield the desired normal output. This calculation was made once every 200 msec. In addition to being either additive or multiplicative in nature, equations could either weight the two inputs equally (Equations 1 and 2) or they could weight the first input more heavily than the second (Equations 3 and 4). That is, the coefficients

multiplied by the inputs were either the same or different. In all, then, there were four basic system dynamics used in the study--equal-additive (Eq. 1); equal-multiplicative (Eq. 2); unequal-additive (Eq. 3); and unequal-multiplicative (Eq. 4). However, The characteristics of the weighting coefficients was a factor manipulated between subjects.

Table 1

System dynamics used to generate normal outputs, along with equations representing the dynamics used to produce system failures.

	Normal	Failure
1. equal-additive	$aI1 + aI2 = 0$	$-cI1 - cI2 = 0$
2. equal-multiplicative	$aI1 + aI2 + bI1I2 = 0$	$-cI1 - cI2 - cI1I2 = 0$
3. unequal-additive	$aI1 + bI2 = 0$	$cI1 + dI2 = 0$
4. unequal-multiplicative	$aI1 + bI1I2 = 0$	$cI1 + dI1I2 = 0$

I1 = Input 1; I2 = Input 2; 0 = output; a, b, c, and d are coefficients where $a > b > c > d$.

Failures were produced by a gradual ramp change in the system equations from a normal to a failed value. The right half of Table 1 lists the equations that were used to produce a simulated system failure. The same failure equation was always associated with a similar normal operation equation (i.e., those on the same row in table 1). Thus, for example, a failure of an $aI1 + aI2 = 0$ system was always of the form $-cI1 - cI2 = 0$. That is, the additive or multiplicative nature of the system, as well as the equal versus unequal weightings of the inputs remained constant during a failure. Only the coefficients themselves varied.

The occurrence of a failure was produced by adding the output of the failure equation to the output of the associated normal equation. In order to avoid a discrete jump in the value of the displayed output variable at the onset of the failure, a slowly increasing "failure coefficient" was first multiplied by the failure output before this value was combined with the normal output to yield the output displayed to the subject. The result of this procedure was a displayed output value that progressively deviated from the normal output the subjects had been taught to expect. As soon as the subjects indicated that a failure had occurred, the system was reset to the normal value shown in the left column equations in Table 1. If the subject failed to identify the failure, the output continued its trend toward greater and greater deviation until the output value eventually became fixed at a preset maximum or minimum value. The time for the failure to ramp to the minimum or maximum value averaged approximately 16 seconds. Failures were set to occur at random intervals ranging from 20 to 40 seconds after the previous failure detection or from the onset of the trial.

Figure 4 illustrates both the normal operation and the occurrence of a failure in an equal-additive (Equation 1) system. Although output values were actually calculated and displayed five times per second, the frames shown in Figure 4 represent what the display would look like if viewed at 5 second intervals during part of a trial. The same normal and failure operation is shown, in parallel, with both a bar graph and a triangle. From 0 - 15 seconds, the output (i.e., the height of the rightmost bar in the bargraph or the height of the triangle) represents an averaged value of the

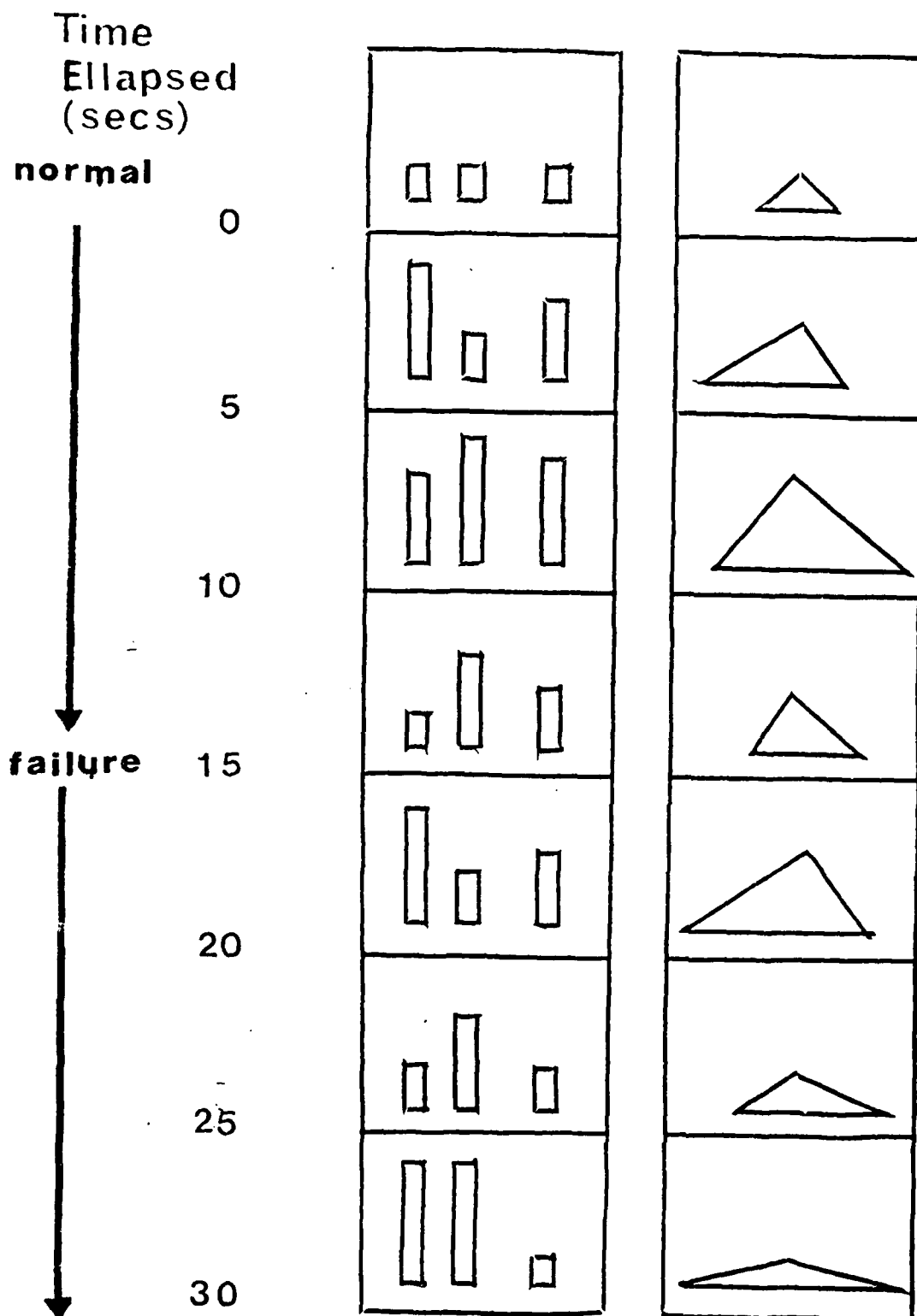


Figure 4: Example of a 30-second sequence during a trial, including normal system operation (0-15 secs) and a failure (15-30 secs). Both bargraphs and triangles represent equivalent input and output values.

two inputs. when a failure occurs on the fifth frame (20 seconds), the output deviates from the normal average value to a value progressively less than would be predicted.

Apparatus

A Hewlett-Packard 8 X 10 cm CRT was used for presentation of the displays. The generation of the stimuli and the collection of data were controlled by a PDP 11/40 computer. Both displays, when representing the largest I/O values, subtended 5.3 X 3.3 degrees of visual angle. The amplitudes and velocity changes of each of the display parameters was similarly matched across the two displays. Subjects performed the monitoring task in a light and sound-attenuated booth, communicating with an experimenter by means of an intercom. Subjects indicated the detection of a failure by pressing one of two keys mounted on the right armrest of their chair. The rightmost key was pressed to indicate a failure in the system displayed to the right, and the left key was used to indicate a failure for the left system.

Procedure

Subjects were assigned to one of three groups, each group learning to monitor a pair of systems which were unique in either their I/O dynamics or input increment size. The systems learned by the three groups, listed in order of predicted difficulty (from easiest to most difficult), differed in the following ways:

Group 1--Equal values were multiplied by both input values for both additive and multiplicative systems (Equations 1 and 2 from

Table 1). Failures resulted in an output value that was increasingly lower than it should be.

Group 2--Equations 1 and 2 were again used to control normal and failure outputs. However, input increment values were three times greater than for Group 1 (i.e., display velocity was increased).

Group 3--Inputs were not equally weighted for either multiplicative or additive systems (Equations 3 and 4). Failures produced outputs that were increasingly greater than they should be.

Each of the groups were exposed to the same four experimental conditions. These conditions were formed by combining the two I/O functions (multiplicative vs. additive) with the two display types (bar vs. triangle). Thus, subjects performed four types of trials: additive-bar graph; additive-triangle; multiplicative-bar graph; and multiplicative-triangle. On any one trial, both systems monitored were displayed using the same format and were characterized by the same normal and failure dynamics.

Each of the subjects completed three two-hour sessions. The first of these sessions was devoted to training, with subjects being shown the defining system equations, graphical representations of the relations among system variables, systems operating in a normal fashion, and systems in operation with the occurrence of failures indicated by supplementary visual cues. The experimenter also quizzed the subjects to determine if they could explain why a system was incorrect when a failure was indicated. By the end of the session, subjects were able to perform a test trial with each display type utilizing both the multiplicative and additive functions. Equal

emphasis was given to both displays and functions, and the order in which the four trial types were learned was counterbalanced over subjects.

The two experimental sessions began with two warmup trials. These were followed by 12 five-minute trials which were broken up into four blocks of three. Each block contained trials of only one display by function condition. At the end of each trial the subjects were provided feedback concerning their false alarm rates, number correct, and median reaction times. Due to the intrinsic nature of the system failure dynamics in which the deviation of the outputs from normal gradually increased or decreased, thus making the failures progressively more salient, almost all failures were eventually detected. Because of this constraint, latency and number of false alarms were calculated as the main dependent measures.

Results

Statistical analyses were conducted on two dependent measures--median latency to detect failures (to the nearest centisecond) and mean number of false alarms per five-minute trial. These variables were summarized for each subject by taking the mean for all replications of a single experimental condition for a given session. These summarized values were then analyzed by means of a five-way mixed-factor ANOVA. There were two grouping (between-subject) factors--gender and system complexity. All subjects, regardless of system complexity group, were exposed to three additional (within-subject) factors--display (triangle vs. bar graph), I/O function (additive vs. multiplicative) and session (i.e., practice).

Preliminary analysis revealed that gender was not a reliable source of variation for either false alarm rates or reaction times; hence, gender was excluded from all subsequent analyses, and data from males and females were pooled.

Figure 5 illustrates the latencies obtained for each display type and I/O function in each of the three system complexity groups. Figure 6 presents the mean false alarm rates in the same conditions. The manipulation of display produced a main effect on latency with the triangle display consistently resulting in quicker failure detections ($\bar{M} = 5.45$ sec) than did the bar graphs ($\bar{M} = 6.21$ sec) ($F(1,21) = 20.83$, $p < .0005$). This effect did not interact with group, I/O function, or session. No difference was found for either display, however, when false alarm rates were analyzed. The false alarm analysis did reveal one three-way interaction involving display type, I/O function, and session ($F(1,21) = 4.56$, $p < .05$). Additional analysis of the simple interaction effects revealed that during Session 1, there was an interaction of display type and I/O function ($F(1,21) = 4.87$, $p < .05$) such that for additive trials the use of the bar graphs resulted in lower false alarm rates ($\bar{M}(+) = .19$; $\bar{M}(*) = .29$). During multiplicative trials, however, use of the triangle displays resulted in fewer false alarms ($\bar{M}(+) = .64$; $\bar{M}(*) = .47$). This interaction of I/O function and display was not found during the second session ($F(1,21) < 1$).

The between-group manipulation of difficulty led to a reliable main effect on both independent measures, as did the within-subject manipulation of I/O function. Although failure detections for the multiplicative systems

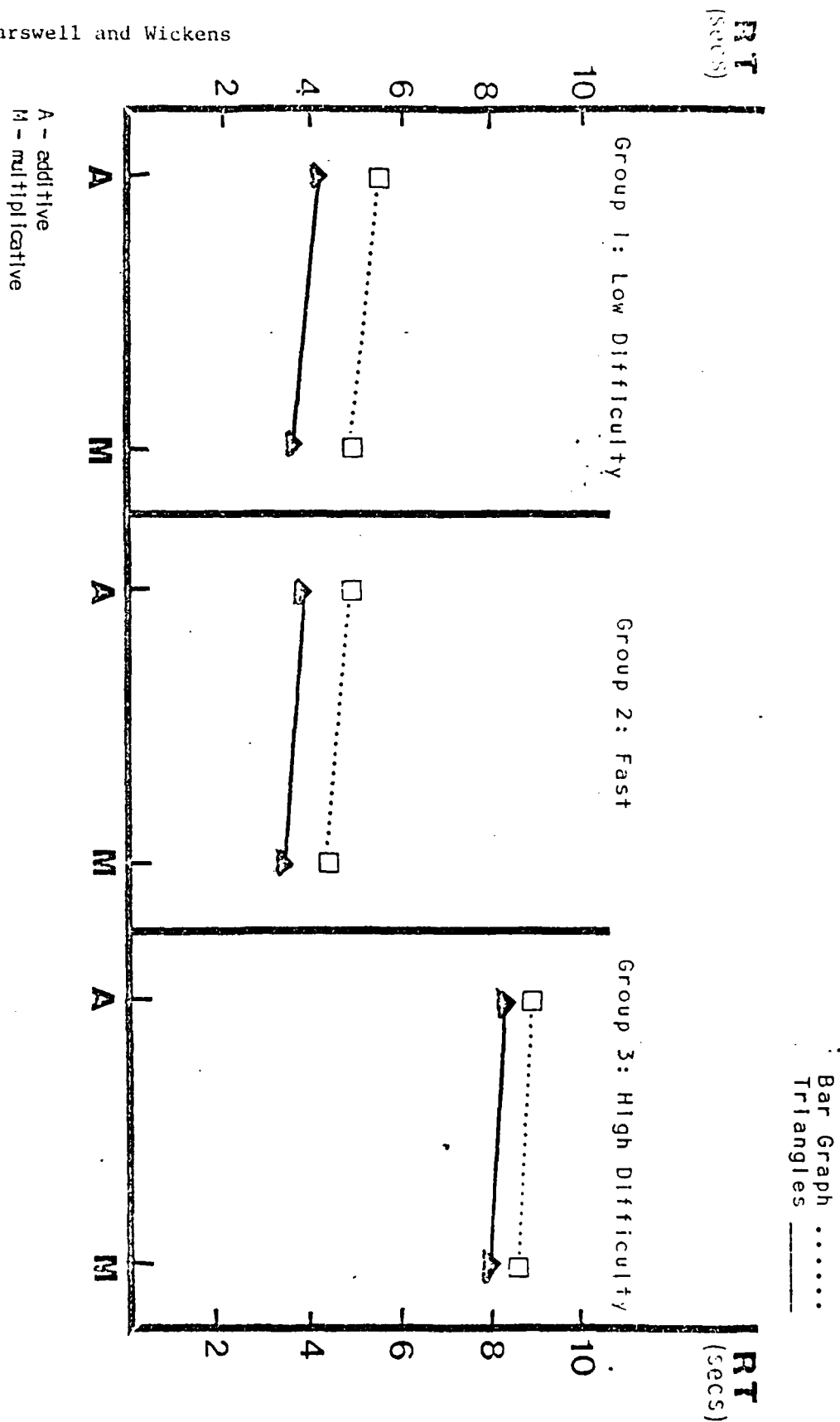


Figure 5: Mean latencies for failure detections at each group x function x display condition.

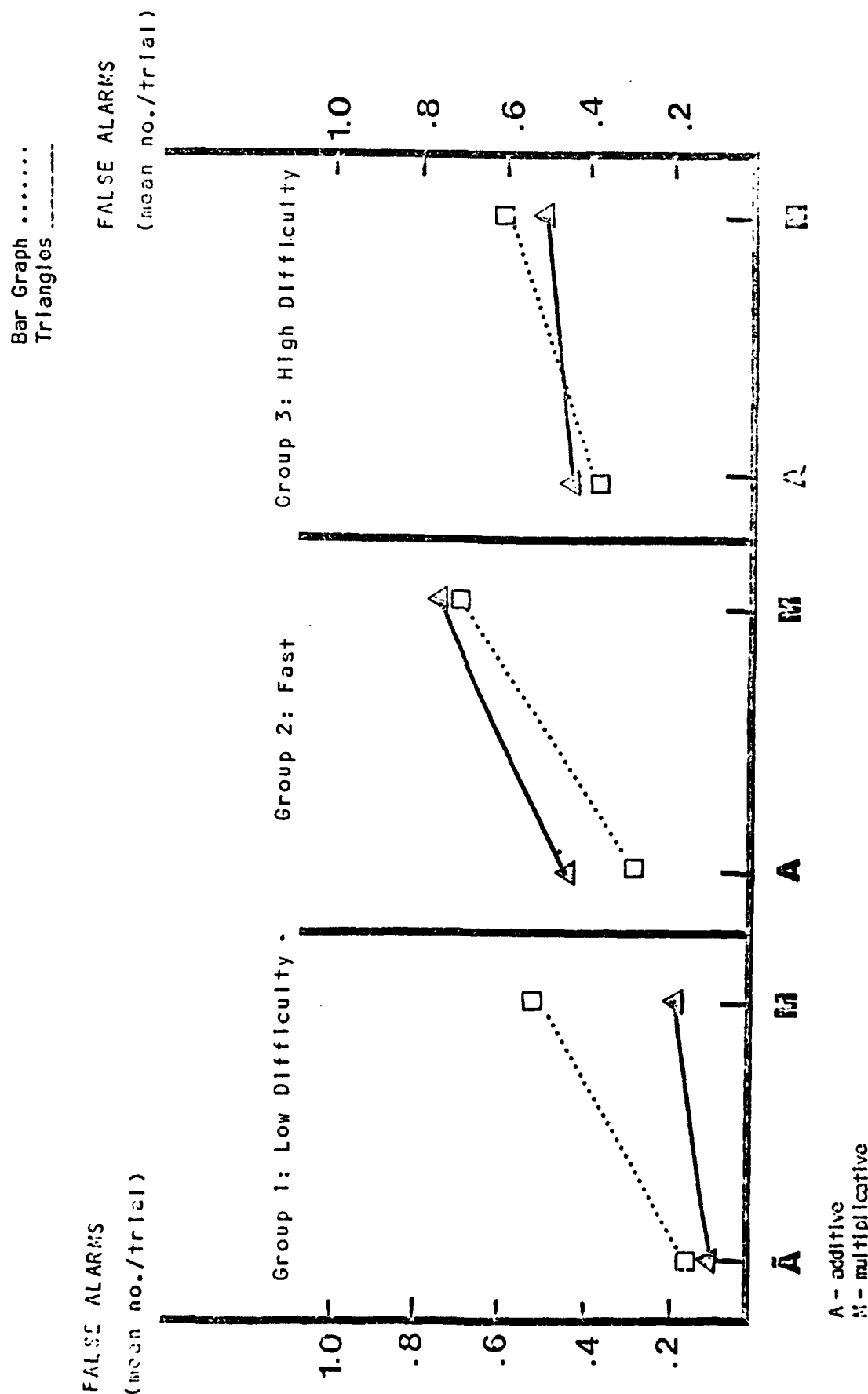


Figure 6: Mean false alarms per trial for each group x function x display condition.

were more rapid ($\bar{M} = 5.60$ sec) than were those for the additive system ($\bar{M} = 6.06$ sec) ($F(1,21) = 11.7$, $p < .005$), the main effect was in the opposite direction for number of false alarms, indicating reduced accuracy for the multiplicative systems ($\bar{M}(+) = .28$; $\bar{M}(*) = .53$; $F(1,21) = 12.03$, $p < .005$). This finding suggests a speed-accuracy tradeoff where subjects responded faster to multiplicative systems failures, but were more likely to respond prematurely.

With regard to the system complexity effect obtained across groups ($F(2,22) = 50.63$, $p < .0001$), the two groups monitoring systems with equally weighted input values produced the quickest responses, mean latencies being 4.49 and 4.33 for Groups 1 and 2, respectively. Group 3, monitoring systems with unequal input weightings, took by far the longest time to respond ($\bar{M} = 8.69$ secs). With regard to false alarms, Group 1 (monitoring the slower system) again showed superior performance with a mean of .18 false alarms per trial. The remaining two groups had greater numbers of false alarms, Group 2 (monitoring the faster system) having an average of .48 and Group 3 having an average of .54 ($F(2,21) = 5.98$, $p < .01$). Group 1, then, was both fast and accurate, while Group 2 was also fast but was less accurate, and Group 3 was both slow and inaccurate.

Discussion

The major conclusion of the present study is that the use of the more integral triangle display was associated with superior performance across a number of integration tasks, each varying in degree of difficulty. The lone

exception to this generalization involved the lower false alarm rates obtained while using the bar graphs to monitor additive systems. This result was obtained, however, only during the first experimental session. Such an effect was not found when the subjects were more experienced. It should be noted that the superiority of the triangle display as reflected in latencies was impervious to any such practice effect. The main effects of the other variables under consideration, whether the system was additive or multiplicative, and the speed and difficulty of the dynamics, were not of fundamental interest to the hypothesis under investigation. Rather, they serve to demonstrate that the advantage observed with the object display is a fairly general one that is maintained across different circumstances.

These findings add credence to the contention of Wickens and Boles (1983) that the degree of task integration is an important delimiter for the use of certain types of displays. In addition to the present findings, two other studies have obtained evidence suggesting the importance of task integration. Boles and Wickens (1983), for instance, looked at the relationship between task integration and the relative benefits of homogenous vs. heterogeneous formatting of visual displays. A homogenous display was defined in this study as a display in which all task-relevant parameters were displayed in a single format (i.e., all elements were either analog or all were verbal). A heterogeneous display was mixed such that one information source was analog and the other was verbal. The study concluded that when there was no need to integrate the two information sources (a dual task condition), the heterogeneous display was associated with superior

performance. On the other hand, when integration was required, it was better to display the two information sources in a homogeneous fashion.

In a second experiment (Wickens, Goettl, & Boles, 1984), subjects performed an air traffic control task in which they monitored the position of several aircraft. Periodically, an aircraft would request to make an altitude change. The subject's task was to grant or deny permission to the imaginary pilot dependent on whether the requested change would bring the craft into a collision course with another plane. The independent variable of interest was whether the request to change altitude was displayed in the same or different format as the information regarding aircraft locations. Results indicated that performance was superior when all information was presented visually rather than bimodally. However, when the need to integrate information regarding altitude change with present aircraft location was removed (i.e., when the two attributes were processed as separate tasks), there was no longer any difference between the two modalities. Thus, the necessity of integrating the different sources resulted in better performance with a homogenously formatted display, while dual task performance eliminated this advantage.

Taken together, the results of the present experiment along with the two experiments on homogenous vs. heterogenous display formatting suggest that the degree of integration required in a task may be an important predictor of the benefit to be gleaned from different formatting techniques. In the present case, task integration may be a requirement for object displays to be truly useful. However, in order to fully test this

hypothesis, both integral object displays and more seperable displays must be studied in cases were multiple information sources are displayed but do not require integration. As predicted by Figure 2, the more seperable graphical techniques should be associated with superior performance in such a situation or, at the very least, should not be appreciably worse than object displays. If such results are obtained, the implications for design would be twofold. First, as previously noted, object displays are not unconditionally better displays than some of the more traditional multivariate techniques, but are simply better displays in certain situations. Secondly, the situations in which object displays do in fact facilitate the communication from machine to human are those in which the human is required to integrate the multiple information sources into a single mental model in order to adequately supervise the system.

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